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The Frequency of T Tauri Companion Stars[1]

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ABSTRACT. We present the results of a magnitude-limited ($K \Leftarrow 8.5$ mag) multiplicity survey of T Tauri stars in two nearby star-forming regions, Taurus–Auriga and Ophiuchus–Scorpius. Each of the 69 stars in the sample was observed at K (2.2 μm) with an infrared array camera on the Hale 5-m Telescope at Palomar Observatory and imaged using two-dimensional speckle imaging techniques. Thirty-three companion stars were found of which 15 were new detections. One of the main results of this survey indicates that the binary star frequency in the projected linear separation range 14 to 225 AU for T Tauri stars ($59 \pm 16\%$) is a factor of 3.5 greater than that of the solar-type main-sequence stars ($17 \pm 3\%$). Given the limited angular separation range of this survey, i.e., both the spectroscopic and wide binaries are missed, the rate at which binaries are detected suggests that *most, if not all, T Tauri stars have companions.* We propose that the observed overabundance of companions to T Tauri stars relative to their older counterparts on the main sequence is an evolutionary effect; in this scheme triple and higher order T Tauri star systems, which are observed at higher frequencies than for the solar-type main-sequence stars, are disrupted by close encounters with another star or system of stars.

I. INTRODUCTION

T Tauri stars are a class of young, low-mass (0.1 to 3.0 $M_\odot$), pre-main-sequence stars whose age is in the range of 10^4–10^7 yr. Although most evolutionary theories of how T Tauri stars emerge from the deeply embedded protostellar stage and progress toward the main sequence are based on single star scenarios (e.g., Adams et al. 1988), surveys of main-sequence stars have already shown that about 2/3 of the solar-type stars are in multiple star systems (Abt and Levy 1976; Abt 1983; Duquennoy and Mayor 1991). So the question arises of how and when these multiple star systems form, for they appear to be the norm as opposed to the exception. The early work of Joy and Van Biesbroeck (1944) showed that 5 of the first 11 known T Tauri stars were binary stars, which suggests that multiple star systems are formed early on in the star formation process. Since 1944 more than 450 T Tauri stars have been identified (see, e.g., Herbig and Robbin-Bell 1988), but only recently has the question of how many of these stars are in multiple systems been revisited.

Recent surveys, which have begun to reveal T Tauri companion stars, include lunar occultations (Simon 1992; Simon et al. 1992; Leinert et al. 1991), radial-velocity measurements (Mathieu 1992; Mathieu et al. 1988), direct imaging work (Simon et al. 1992; Zinnecker et al. 1992), and speckle imaging work (Leinert et al. 1992). Figure 1 shows the distribution of solar-type main-sequence stars (Duquennoy and Mayor 1991) transcribed to be a function of angular separation if all the stars were located at 150 pc, the approximate distance to many nearby star forming regions. Each technique is sensitive to a unique limited range of binary star separations. Thus the different surveys are complementary, since a combination of several methods of detection is necessary to deduce what fraction of young stars have companions.

We have carried out a magnitude limited survey of T Tauri stars using the technique of speckle imaging. If T Tauri stars have the same binary star frequency distribution as their older counterparts on the main sequence (Fig. 1), then speckle imaging is an ideal technique for finding companion stars because it is sensitive to the peak of the binary star frequency distribution.

In interpreting the results of this survey, one can compare the multiplicity statistics of (1) T Tauri stars in the two different star forming regions; (2) T Tauri stars with and without evidence of inner accretion disks; and (3) T Tauri stars and solar-type main-sequence stars. This paper concentrates on the last comparison in the interest of understanding the multiplicity as a function of age. A more complete discussion of this survey can be found elsewhere (Ghez 1992).

2. TECHNIQUE AND SYSTEM

Speckle imaging is a technique used to recover diffraction-limited images from data obtained in the presence of atmospheric turbulence. The details of the data analysis are not given here, but can be found in Ghez (1992).

The data for this survey were obtained at the $f/415$ Cassegrain focus of the Hale 5-m telescope on Palomar

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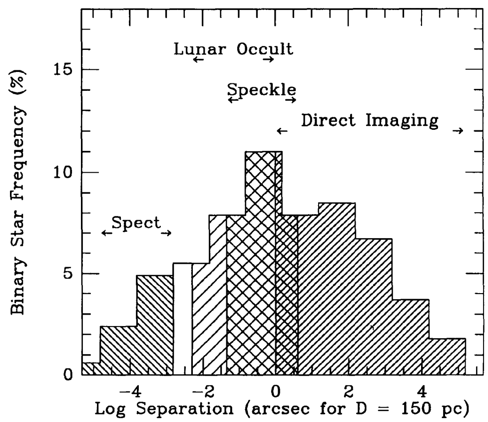

FIG. 1—The distribution of solar-type main-sequence stars (Duquennoy and Mayor 1991) as a function of angular separation, if all the stars were located at 150 pc, the approximate distance to many nearby star forming regions. Also shown is which region techniques such as spectroscopy, lunar occultations, speckle imaging (at 2.2 μm on a 5-m telescope), and direct imaging are sensitive to.

Mountain using a 58×62 InSb array camera in the photometric K (2.2 μm) band. The pixel scale, determined by observing and reconstructing images of several binaries with well-known orbits (McAlister and Hartkopf 1988), is 0″.053×0″.053 (±0″.001). This system was sensitive to binary stars with separations between 0″.1 to 1″.8 for this survey, where the lower limit was set by the diffraction limit of the telescope and the upper limit was set by the field of view of the array.

3. SAMPLE

This survey was confined to the two nearest star-forming regions observable from the northern hemisphere, Taurus–Auriga (140 pc, Elias 1978) and Ophiuchus–Scorpius (125 pc, de Geus et al. 1989). At the distances to these star-forming regions, this survey's angular binary star separation range, 0″.1 to 0″.8, corresponds to a common projected linear separation range of 14 to 225 AU.

The compilation of Herbig and Bell (1988) and recent X-ray selected source lists (Bouvier and Appenzeller 1991; Walter 1990) were used to identify a total of 143 T Tauri stars in the regions of interest. Seventy-four of these stars had a K magnitude brighter than 8.5 mag (the limiting magnitude of the speckle system used) and of these 69 were observed over the period 1990 July to 1991 November.

4. RESULTS

Among the 69 target objects observed, we detected 31 binary and one triple system; 15 of these were previously unreported. These multiple star systems were all assumed to be physically bound since the probability of chance alignment with a star field within 1″.8 of a target star is negligible for both regions.

We defined the binary star frequency to the number of companion stars, within the specified separation range, per

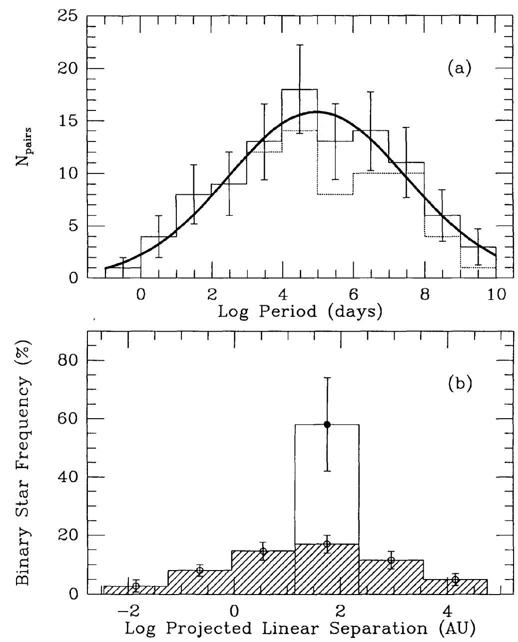

FIG. 2—(a) The distribution of companion stars in the nearby sample of solar-type main-sequence stars as a function of orbital period, taken from Duquennoy and Mayor (1991). (b) The hatched histogram is the binary star frequency of the solar-type main-sequence stars as a function of average projected linear separation. Also shown is the binary star frequency of the T Tauri stars (the unhatched region). The T Tauri binary star frequency appears to be a factor of 3.5 greater than that of the solar-type main-sequence stars.

the number of systems examined. After accounting for nonuniform dynamic range between the observations and the number of independent targets (see Ghez 1992), the binary star frequency in the projected linear separation range 14 to 225 AU for this survey is 59±16%.

5. DISCUSSION

The results of this survey indicate that a large fraction of T Tauri stars have companion stars. The youth of this population of stars ($<\sim 10^7$ yr) suggests that multiple star systems are produced during the early stages of star formation. To study in greater detail questions regarding when multiple star systems form and the early evolution of these systems, we compared the multiplicity of the T Tauri stars in this sample with their older counterparts on the main sequence. To do this, we selected Duquennoy and Mayor's (1991) survey of nearby solar-type main-sequence stars as a comparison sample.

Duquennoy and Mayor (1991) searched a total of 164 nearby solar-type main-sequence stars for companion stars and found that the number of companion stars as a function of the orbital period P could be fit by a Gaussian distribution in log P. Figure 2(a) reproduces their binned bias corrected data as well as their model fit. To compare this work to the T Tauri star sample, we converted their distribution, which is a function of P, to a function of average projected linear separation ($\langle a \rangle$). This was done in several steps: the first step converted P to its corresponding semimajor axis A using Kepler's law. This conversion requires an estimate of the total mass in these systems. For this solar-type main-sequence sample, the average primary star mass is 1 $M_{\odot}$ and the average mass ratio, which was calculated from Duquennoy and Mayor's Fig. 10, is 0.40. Thus the conversion of P to A assumed an average total mass of 1.4 $M_{\odot}$. The second step translated A to $\langle a\rangle$ based on a Monte Carlo simulation carried out by Fischer and Marcy (1992), which gave the following relationship:

$$A=1.26\langle a\rangle.$$

These steps resulted in the following relationship to convert orbital period to average projected linear separation:

$$\log P_{\text{days}}=\log\langle a\rangle_{\text{AU}}+2.64.$$

The distribution of solar-type main-sequence star companion stars as a function of $\langle a\rangle$ was then rebinned, using Duquennoy and Mayor's model fit, such that the new bin width matched our separation range ($\Delta \log\langle a\rangle_{\text{AU}}=2.2$). Figure 2(b) shows the result of the the final step, which normalized their distribution by the total number of target stars (164) to produce a binary star frequency distribution. Integrated over the project linear separation range 14 to 225 AU, the binary star frequency of nearby solar-type main-sequence stars studied by Duquennoy and Mayor (1991) is 17±3%, compared to 59±16% for the T Tauri stars. *Thus the T Tauri binary star frequency appears to be greater than that of the main-sequence stars by a factor of 3. The discrepancy between the two binary star frequencies is a 3σ effect.*

If the difference in the binary star frequency between the T Tauri stars and their older counterparts on the main sequence is due to an intrinsic difference in their properties (i.e., it depends on their age), then the stars in the current T Tauri star sample will have the same properties as the solar-type main-sequence sample once they evolve down to the main sequence. We explored two possible evolutionary scenarios that might explain the putative overabundance of companion stars at the younger stage of evolution in the projected linear separation range 14 to 225 AU.

The first investigation considered the possibility that T Tauri stars and solar-type main-sequence stars have the same number of companion stars integrated over all possible separations. In this case an overabundance of companion stars in the T Tauri sample with respect to the solar-type main-sequence sample in the projected linear separation 14 to 225 AU requires a deficiency of T Tauri star companion stars outside this range so that the integrated number of companion stars would be the same for both samples. The observed difference would then be the result of a more peaked distribution for the T Tauri stars, as opposed to a difference in the overall binary frequency. This implies that the distribution of binary stars as a function of separation would spread or relax as a function of time. Integrated over all separations, the binary star frequency for solar-type main-sequence stars is 62±6%. This is comparable to the binary star frequency of T Tauri stars in the limited projected linear separation range 14 to 225 AU. If this hypothesis is true, then only 2(±11) companion stars should be found in the complete sample outside the separation range 14 to 225 AU. Sixteen companion stars have already been detected outside this separation range (with other detection techniques), even though the current knowledge of companion stars for this sample at all separations is far from complete. It therefore appears that the total number of companion stars is greater than the T Tauri stage of evolution than on the main sequence.

If there is an overabundance of companion stars integrated over all separations among the T Tauri stars as compared to the solar-type main-sequence stars, then some of the current T Tauri star pairs must be disrupted by the time they evolve to the main sequence. One possible mechanism is the disruption of young triple or higher order systems, in which the system is "ionized" by close encounters with another star or system of stars.

It is worth stressing the importance of observing the *same* sample with many *different* techniques. This is necessary to determine the frequency of double, triple, and quadruple systems, because the various components of a given system will not all be observed with any one technique. This incomplete overlap of our sample with other techniques has already revealed that 14% of the target stars in our sample are members of systems with three or more components, whereas Duquennoy and Mayor (1991) find that only 5% of their solar-type main-sequence targets are members of these higher-order systems. The triples and quadruples that have been observed so far are all in hierarchical systems, i.e., the ratio of separations in the system is large ($\geqslant 10$). If disruption occurs, then the more widely separated stars (or pair of stars) would be more likely to break away. Thus one would expect to observe no difference between the T Tauri and the main-sequence binary star frequencies at the shortest separation. This is consistent with current spectroscopic measurements of T Tauri stars, which reveal a binary star frequency at the shortest periods ($P<$ 100 days), or equivalently at the smallest separation, that is similar to that of the solar-type main-sequence stars (Mathieu et al. 1988; Mathieu 1992). Thus if the 3σ discrepancy between the number of companion stars observed for the T Tauri stars and the solar-type main-sequence stars is real, the disruption of triple and quadruple systems may provide a satisfactory evolutionary scenario.

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